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ABSTRACT

This paper presents a model for systematic instructional design that includes mental model analysis together with the procedures used in developing computer-based instructional materials in the area of statistical hypothesis testing. The instructional design model is based on the premise that the objective for learning is to achieve expert-like mental models, and instruction should be designed to help learners build relevant mental models in the specific domain. (The term mental model is defined as a person's internal, domain-specific representation that may be incomplete or unstable, and the term relevant mental model is defined as an internal, domain-specific representation that is relevant and useful for a person's subsequent understanding of and problem solving in the field.) It is proposed that mental model analysis be integrated into the design of instructional materials so that cognitive task analysis can be used to produce effective instructional strategies. The three phases in the design of instruction covered by the model are described: (1) analysis of instructional outcomes; (2) development of instructional material; and (3) implementation, evaluation, and revision of the instructional material. Seven procedures for applying this model are discussed in more detail: (1) identify instructional goals/objectives; (2) conduct mental model analysis; (3) identify the learners' entry level knowledge/skills; (4) develop instructional strategies considering mental models; (5) develop instructional materials and tests; (6) formative evaluation; and (7) revision of the instructional program. A discussion of the instructional effects which resulted from the application of the mental model strategies in an introductory statistics course concludes the paper. (2 figures, 32 references) (BBM)

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Title:

Effects of Instructional Design with Mental Model Analysis on Learning

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Abstract

This paper discusses the need for integrating mental model analysis in the process of instructional program development. Investigations into the effects of mental models strategy have indicated positive effects on learning and instruction. It was proposed that in developing instructional materials which require complex cognitive process in learning, the instructional designer identify the integrative goals/objectives along with their component declarative and procedural knowledge, and develop instructional strategies that can help learners acquire integrated outcomes such as relevant mental models in the specific domain. The procedures and examples of the instructional materials development with mental model analysis are illustrated.

Effects of Instructional Design with Mental Model Analysis on Learning

The concept of mental models (Wilson & Rutherford, 1989; Norman, 1986) has recently been introduced to the field of instructional psychology along with other constructs of knowledge representation such as schemata (Rumelhart, 1980), frames (Minsky, 1975), or scripts (Schank & Abelson, 1977). Investigations into the effects of mental models strategy in relation to learning and instruction have been conducted in various domains (Dyck & Mayer, 1989; Gentner & Stevens, 1983; Mayer, 1989; Kieras, 1987; White & Frederiksen, 1986). Mayer, Dyck, and Cook (1984), for example, investigated the effects of mental models on performance in causal systems. They provided node training which is the conceptual underpinnings of the key definitions involved in the passage, and link training provided by passages that emphasized the main relations among concepts. They predicted that subjects who were provided with the mental models aids would build a coherent mental model of the system. Compared to the control group, the mental model group significantly recalled more information concerning the main concepts and their relationships, and performed better in creative problem solving.

In a study by Kieras and Bovair (1984), subjects who knew how a control device worked could learn and infer how to operate it much more efficiently than subjects who did not have this information. In their experiment, the mental model group, who were exposed to the device model that describes the internal mechanism of the device before receiving the procedure training on how to operate a control device, learned the procedures faster, retained the procedures more accurately, and executed the procedures faster than the rote group. These results support instructional strategies that help learners build mental models, which will, in turn, promote subsequent learning and problem solving.

Streitz (1988) distinguished a mental model from a conceptual model in that a mental model is a subjective knowledge representation that is an idiosyncratic and very personal model, while a conceptual model is a model developed by scientists or designers. In studies of instructional applications of mental models, Mayer

(1989) concluded that by using conceptual models, which are words and/or diagrams that are intended to help learners build mental models of the system being studied, learners could improve their recall of conceptual information and increase their creative solutions on transfer problems.

In the present study, the author reserves the term mental model for a person's internal, domain-specific representation which may be incomplete or unstable, and the term relevant mental model for an internal, domain-specific representation that is relevant and useful for a person's subsequent understanding and in problem solving in the domain.

This paper presents a model for systematic instructional design that includes mental model analysis, and the procedures used in developing computer-based instructional materials in the area of statistical hypothesis testing. The instructional design model is based on the premise that the objective of learning is to achieve expert-like mental models, and instruction should be designed to help learners build relevant mental models in the specific domain. In addition, the instructional effects which resulted from the application of the mental model strategies in the domain of introductory hypothesis testing are discussed.

A Model for Instructional Systems Design with Mental Model Analysis

The quality of an instructional system would be considered high when adequate contents are presented to learners using proper instructional strategies. In a recent discussion on integrative goals for instructional design, Gagné and Merrill (1990) suggested the integration of multiple objectives for comprehensive purposeful activities. They considered integrated objectives as an enterprise, and proposed that integrative goals be represented in cognitive space by enterprise schemas (similar to the concept of mental models) whose focal integrating concept is the integrative goals.

As Gagné and Merrill (1990) suggested that instructional design must specify the conditions for acquisition of enterprise schemas or mental models, the

content/task analysis which emphasizes on mental models are expected to lead to considerable changes in instructional strategies and material development. Thus, the author proposes that mental model analysis be integrated as one of the phases in the systematic design of instructional materials so that cognitive task analysis can produce instructional strategies, which provide conditions for learners to build relevant mental models in the domain.

Phases of Systematic Design of Instructional Materials

The model described in this paper is categorized into three phases in a systematic design of instruction: (1) analysis of instructional outcomes, (2) development of instructional material, and (3) implementation, evaluation, and revision of the instructional material.

Phase I: Analysis of instructional outcomes. In this phase, information about the resulting outcomes are to be provided. After the overall instructional goals are identified, relevant mental models for the domain will be determined through cognitive task analysis (i.e., mental model analysis). The mental model analysis identifies declarative and procedural knowledge involved in the domain, and determines whether mental model strategies would be helpful in the particular domain. The end results of this phase would be the determination of the relevant mental models for teaching learners.

Phase II: Development of instructional material. To ensure optimum learning, learners' entry level knowledge and skills are first identified in this phase. Using the information on the learners' entry level and the relevant mental models for teaching novices, instructional strategies to help learners build relevant mental models of the domain will be developed. Employing both macro and micro levels of instructional design strategies (Reigeluth, 1983), as well as the mental model strategies developed in this phase, instructional materials are developed along with the selection of appropriate media to deliver the instruction. Methods for assessing the learners' performance are also developed. In other words, whether learners acquired relevant mental models or not should be measured through appropriate assessment procedures.

Phase III: Implementation, evaluation, and revision of the instructional material. In this phase, the instructional materials developed in phase II are implemented for evaluation. The effectiveness and practical feasibility of the instruction are to be revealed through the formative evaluations (Dick & Carey, 1985), and necessary revisions should be made according to evidence from the evaluation. In the following section, each step of the model for the systematic design of instructional material is described.

Procedures for Developing Instructional Materials

Figure 1 presents a model of systematic approach to instructional materials development. In this paper, the emphasis is given on the application of mental model analysis to each step in describing the procedures for instructional materials development.

Insert Figure 1 about here

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1. Identify instructional goals/objectives

Goals may be stated as the intended outcomes of instruction. In specifying learning outcomes, Gagné, Briggs, & Wager (1988) suggested that assigning learning objectives to five major categories of human capabilities (i.e., intellectual skills, cognitive strategies, verbal information, motor skills, and attitudes) can simplify the instructional planning. However, in situations where complex cognitive processes are involved in learning, that is, when instruction involves more than simple rules/procedures or facts, instructional objectives may be specified comprehensively so that the following content/task analysis can be conducted to provide learning conditions for comprehensive activities. For instance, in developing instructional materials for teaching introductory hypothesis testing, an example of instructional objectives would be: The students will be able to make inferences about the nature of the population when given problems in hypothesis testing, through specifying null and alternative hypotheses, setting the region of rejection, computing the test statistic, making decisions about the hypotheses, and drawing valid interpretations on the decision made.

This example of an objective indicates that to achieve a higher level of performance in problem solving in this subject matter, the students should have both conceptual and procedural knowledge involved in hypothesis testing, and apply or synthesize that knowledge when they encounter problem-solving situations.

Instructional designers, then, may consider the objectives as coherent cognitive structures of integrated knowledge/skills of the to-be-learned materials, so that the following steps in the design of instruction would focus on the learners' outcomes which are goal-related knowledge and skills, or stated differently, coherent and relevant mental models of the particular domain.

Then, what and how should the specific knowledge or skills be presented to help learners develop the relevant mental models? This question calls for the analysis of mental models in the domain, which is the topic of the next section.

2. Conduct mental model analysis.

The purpose of mental model analysis is to determine relevant mental models for teaching learners in accordance with the instructional objectives specified in step 1. By examining both experts' and less-than-experts' mental models, relevant mental models learners should acquire as well as learners' common misconceptions in the domain will be determined. Figure 2 presents the procedure involved in conducting mental model analysis.

Insert Figure 2 about here

Determining if the mental model strategy can be helpful. To determine if the mental model strategy would help students learn materials in a particular domain, available texts or documents would first be analyzed to specify what knowledge/skills should be taught. In addition, subject matter experts may play a significant role in content/task analysis. Through the content analysis, declarative and procedural knowledge (i.e., facts, concepts, procedures, rules, or

principles) involved in the domain are identified. The result of content analysis may reveal that the particular domain to teach involves, for example, concepts and principles, or it may involve only facts and simple procedures.

Upon the identification of knowledge/skills to be taught, it may be decided whether mental model strategy is helpful in teaching the particular domain. Kieras (1988) identified the situations when mental models are not useful in the domain of device maintenance: (1) if the procedures are easy to learn by rote; (2) if the device is so simple that the learner does not need to make inferences; (3) if mental models are too difficult or complicated for the learner to acquire and use; and (4) if mental models fail to support the inferences that the learner needs to make, or alternatively, support inferences that the learner does not need to make. In his review on the effects of conceptual models that are intended to help learners build mental models, Mayer (1989) focused on reviewing explanative material. Explanative material allows learners to build and use models that explain the information. Mayer (1989) added that the reason he focused on explanative material in his review was because meaningful methods of instruction can only have an effect for learning of material that is potentially meaningful.

Thus, to determine if mental model strategy is helpful, it should be analyzed to find out if the content requires meaningful learning or inferencing process based on knowledge acquired from the instruction. The designer may analyze if the mental model strategy would help learners in selecting information to pay attention to, in organizing incoming information in short-term memory, in integrating prior knowledge from long-term memory with incoming information, and in encoding the resultant learning outcome in long-term memory (Mayer, 1989).

In the domain of introductory hypothesis testing, existing textbooks were first analyzed. The declarative and procedural knowledge involved in hypothesis testing were identified, which were concepts, principles, and procedures involved in hypothesis testing. At this stage, it seemed that there could be a small set of mental models which could be either relevant or incorrect after students are exposed to problems on hypothesis testing.

Relevant mental models to teach. To determine relevant mental models to teach in introductory hypothesis testing, a pilot study was conducted. The procedures included: (1) experts' and intermediates' mental models were elicited; (2) the elicited mental models were compared with the textbook contents analyzed; and (3) the relevant mental model to teach novices were determined. This pilot study is described in detail elsewhere (Hong, 1990).

The results of the pilot study revealed that experts' verbal protocols on the problem solving process were incomplete such that their protocol indicates combined inference steps. This is largely because their knowledge were compiled through their extended learning process and extensive practice in problem-solving activities. However, in considering the learnability of expert models, several additional questions were presented to experts in order to decompile their knowledge, such as, "If you teach students to solve this problem, what would you do?" In investigating the intermediates' mental models, it was found that their mental models were especially useful in designing instruction because their knowledge was not compiled and their common misconceptions were revealed.

The major difference between experts and intermediates in the domain of introductory hypothesis testing was their conceptual understanding: While all experts had a solid conceptual understanding, many intermediates did not. However, the diagrammatic problem representation was useful for most subjects' problem solving, especially for intermediates. Considering the importance of conceptual understanding and usefulness of diagrammatic representation, the mental model to teach novices in the context of introductory hypothesis testing was defined as concepts and rules involved in hypothesis testing in diagrammatic representation.

Research on text illustration supports the use of diagrammatic representation in teaching or learning the instructional materials and solving problems: Students who received instruction such as text passages which include illustrations retained more information than those who received instruction without illustrations (Alesandrini, 1984; Anglin & Stevens, 1986; Curtis,

1988; Reid & Beveridge, 1986; Rusted & Hodgson, 1985). Studies on topologies of device models (de Kleer & Brown, 1983; Kieras, 1984), which used diagrammatic representations of the models, also show the effects of the diagrammatic presentation of the instruction.

3. Identify the learners' entry level knowledge/skills.

The most common method for assessing prerequisite knowledge and skills may be administering a pretest to students. The test may contain items to assess the knowledge and skills students should have when the instructor begins to teach new information (Dick & Reiser, 1989).

In the present hypothesis testing study, prerequisite knowledge/skills that a student should have were identified, and it was decided that a prerequisite learning and test session be provided. The intention underlying the test item development was that the subjects learn the prerequisites by solving problems and reading the informative feedback. The subjects were given the opportunities of answering twice in case they made incorrect responses. Informative feedback was given whether the response was correct or not.

4. Develop instructional strategies considering mental models.

To determine the instructional strategies to help learners build relevant mental models in hypothesis testing, the investigator designed four instructional units about the hypothesis testing for one-sample case for the mean (variance known). The four instructional units basically contained the same information, but were designed in different presentation sequences (separate and combined) and presentation modes (diagrammatic and descriptive). Briefly, the sequencing of the two instructional units, separate-diagrammatic and separate-descriptive units, were the same in that concepts involved in hypothesis testing were presented first, and then followed by procedural and quantitative instruction. For the combined-diagrammatic and combined-descriptive units, the concepts and procedures were presented simultaneously.

The primary difference between the diagrammatic and descriptive presentation modes was the frequency of

the diagrams presented in the instructional units. In the diagrammatic presentation mode, 18 diagrams were presented, while six diagrams were presented for descriptive mode (see Hong & O'Neil, in press, for detail).

The rationale underlying the development of the four units were from the mental model analysis conducted in the earlier stage and the mental model literatures. Discussing the progressions of qualitative models in circuit behavior, White and Frederiksen (1986) advocated that qualitative conception of the domain should be acquired before quantitative models be introduced so that the causal relations in the domain could be obvious. They argue for the importance of presenting, in the initial stages of learning, qualitative, causally consistent models so that students can gain an understanding of basic concepts and principles.

In their study on transfer of computer language comprehensive skill, Dyck and Mayer (1989) conducted a cognitive analysis of BASIC languages. Then they provided sequential and simultaneous instructional methods. In the simultaneous method, the semantics of a language were taught within the syntax of the language, and in the sequential method, the semantics of a language were taught prior to the syntax of the language so that learning of semantic of a language can influence learning of the other language. Results supported the use of a sequential method of programming language instruction, because subjects who had previous experience in the learning of English procedural language (semantics) learned BASIC faster and more accurately.

These studies illustrates that the teaching of concepts prior to procedural/quantitative instruction may help students build relevant mental models. In addition, as discussed earlier, the provision of instruction in diagrammatic forms rather than descriptive forms would facilitate understanding and solving problems.

5. Develop instructional materials and tests.

At this stage the actual instructional messages, such as directions, information presentations, practices, feedback, and test items were written on

paper in draft form. In the selection of media, it was decided that the prerequisite test and instructional units be presented by computer-based instruction (CBI). The rationale for using CBI in statistics was two fold: (1) evidence from the literature indicates that CBI is useful in statistics instruction. For example, Varnhagen and Zumbo (1990) found that computer-assisted instruction had a significant effect on student attitude toward statistics instruction and had an indirect effect over performance through its influence on affect. They recommended that technical courses such as introductory statistics should ideally be supplemented with CBI in order to provide optimal learning experiences; (2) the use of CBI facilitates the research issues, e.g., software ensures that the experimental treatments were provided as designed. Upon completion of written draft of the material, storyboards were produced with each page corresponding to a separate computer screen display. The computer-based instructional materials were programmed in an authoring system, IconAuthor (AIMtech, 1989) and were delivered by an IBM personal computer.

After the prerequisite test and the four instructional units were developed, they were checked to ensure that the instructions were coherent and the program was free of functional errors before the formative evaluation took place. The following issues were considered when the investigator worked through the program (Alessi & Trollip, 1985; Olson & Wilson, 1985):

A. Is the use of words and symbols involved in hypothesis testing consistent throughout the program?
B. Is the spelling, grammar, punctuation, and spacing free of error and consistent?
C. Are the directions properly and clearly given for the subjects to proceed with the experiment?
D. Is the information covered in the treatment complete and accurate, and placed in the proper sequence? And, is the design method used in the study well reflected in the information provided?
E. Are the questions and feedback handled properly?
    1) Are the practice items placed in the proper sequence? In other words, are the practice items related to the information being presented?
    2) Are the questions/practice items unambiguous?
    3) Is the feedback appropriate and increasingly informative after each successive incorrect response?
    4) Are the subjects' performance, i.e., scores, number of attempts, and time to completion, recorded accurately?

F. Is the screen designed properly?
   1) Is the amount of information proper for each screen?
   2) Are the diagrams drawn in the proper place?
   3) Is the type size and style, highlights, inverse, or animation used in an instructional relevant way, but not overused?
   4) Are the feedback messages displayed on the lower part of the screen in a consistent manner?
   5) Is the screen continued from the last screen noted by the heading and continuation remark?
   6) Is the timing of text output relevant or controlled by the subjects?

Posttest items were prepared in paper-and-pencil format because the mode of the posttest was think-aloud protocol. The posttest consisted of 17 problems representing major concepts or rules involved in introductory hypothesis testing. Each problem was typed on a separate sheet and subjects could use the blank space for computation or drawing diagrams while performing the think-aloud protocol.

Coding system for the protocol analyses was developed based on the posttest items and a theoretical framework of relevant mental models in hypothesis testing. In developing the coding categories, no attempt was made to deal with all the information in the think-aloud protocols. Instead, only selected features of the protocols related to the task were included in the categories. Since the present study was aimed at finding if the subjects built relevant mental models in hypothesis testing, a coding system describing the information processing leading to the solution was developed. The categories in the system also included misconceptions found from the pilot study and formative evaluation. The examples of the coding system and scoring procedures can be found in Hong and O'Neil (in press)

6. Formative evaluation.

After the instructional program development was completed and steps were taken to ensure the program was free of functional errors, a two-stage formative evaluation was conducted: one-on-one testing and small-group testing (Dick & Carey, 1985).

<u>One-on-one testing</u>. The purpose of this testing was to revise the instructional program while it was being developed by using students similar to those for whom the lesson was designed. Because of the small

numbers involved in this testing, the information gathered from the testing could only be used to aid further revision, but not for a definitive statement of fact (Alessi & Trollip, 1985). Materials used in this testing were CBI instructional units developed by the investigator.

While each subject worked through the program, the investigator attended the whole session and took notes through unobtrusive observation. The investigator asked the subjects to make comments about the program whenever they encountered difficulty in understanding the directions, presentation, and/or questions. As soon as the subjects finished the treatment session, the investigator discussed with the subjects the comments they made and observations the investigator wrote down.

For the posttest, think-aloud protocol method was employed and recorded for the entire session. After the test, the subjects were asked what they thought of the whole session. Findings from the one-on-one test were used when revisions were made (see Hong, 1990)

Small group testing. After the one-on-one testing, the instructional program including prerequisite test, four treatment units, and posttest items were revised. In this stage of formative evaluation, it was intended to test the revised instructional program and further revise it before the main study. Even though the title--small group testing--was borrowed from Dick and Carey (1985), the testing was conducted at one to one level because think-aloud protocol was employed for the posttest. As with the one-on-one testing, because of the small number of subjects were involved, the information from this testing was used only to guide revision, not for any kind of statistical testing.

In this testing, the subjects were not allowed to ask any questions while studying the material except with the prerequisite test. However, they were encouraged to make notes of comments during the sessions. The investigator sat with the subjects while they studied through the program and took notes of their behavior. A tape recorder was used throughout the posttest session and the subjects were encouraged to think out loud. Findings from the small group testing were used for revision.

7. Revision of instructional program.

Data collected from pilot testing, one-on-one, and small-group testing were used for revising instructional program. In brief, some of test items were revised or deleted; feedback information was elaborated; help screens were added; diagrams were elaborated and explained; and coding categories were revised by analyzing each subject's protocols.

Effects of Mental Model Strategy on Instruction and Learning

To test if the mental model strategies (i.e., separate and diagrammatic presentation) had a positive effect, subjects were drawn from students who were taking introductory statistic courses. The subjects did not have knowledge on the introductory hypothesis testing at the time of the experiment, but had learned the prerequisite information. That is, the experiment was conducted just before the subjects learn the hypothesis testing in their classes. The subjects were grouped into blocks according to their educational levels, i.e., 27 graduates and 29 undergraduates, and a random assignment to each treatment combination was carried out separately for each block of subjects.

An analysis of covariance with a randomized block factorial design was performed on subjects' problem-solving scores. The prerequisite test score was used as a covariate in the data analysis. In addition, an analysis of variance was conducted to examine whether the frequencies of using diagrammatic problem representation differed by the differential treatments of presentation mode and presentation sequence. Data analyses of the study are described in full detail elsewhere (Hong & O'Neil, in press).

The results of the study provide evidence concerning the instructional strategies which help learners build relevant mental models in introductory hypothesis testing. First, providing conceptual instruction prior to procedural instruction significantly facilitated understanding the concepts and the procedures involved in hypothesis testing. Second, instruction using extensive diagrammatic representation facilitated subjects' development of

representational ability for understanding the instruction by building diagrammatic mental models.

Research on mental models has found that the use of mental model strategy can enhance learners' acquisition of knowledge, especially where inference process is necessary (Kieras, 1988; Mayer, 1989). The present study suggests that, in the course of instructional design and development, mental model analysis be conducted to determine appropriate instructional strategies.

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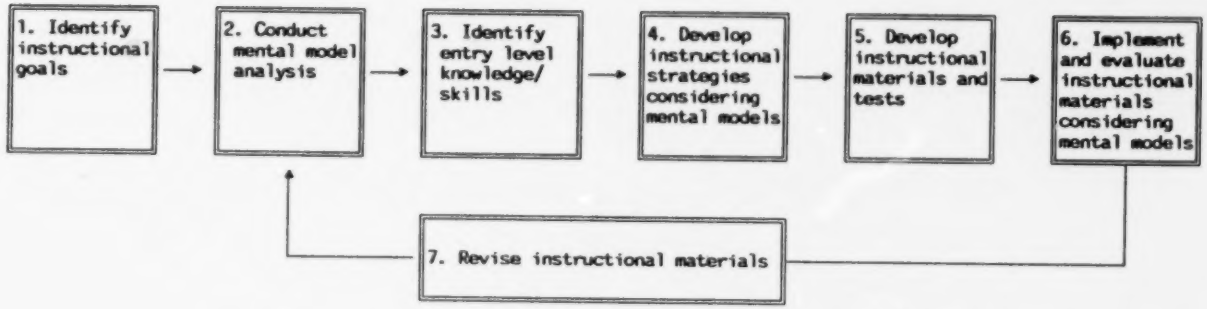
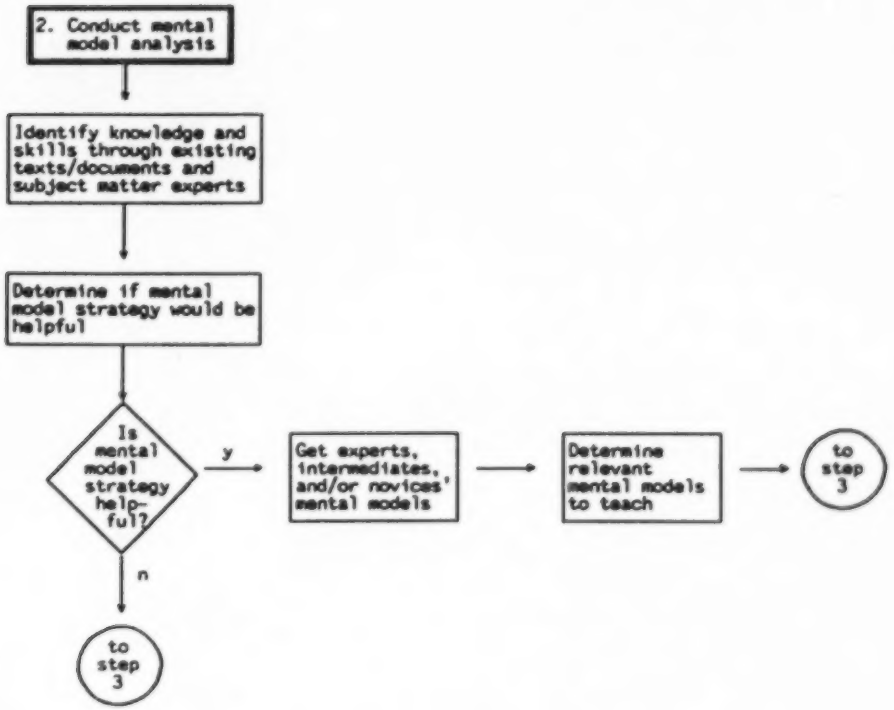
Figure Caption

Figure 1. A model for instructional systems design with mental models analysis.

Figure 2. Procedures for conducting mental model analysis.


1. Identify instructional goals
2. Conduct mental model analysis
3. Identify entry level knowledge/ skills
4. Develop instructional strategies considering mental models
5. Develop instructional materials and tests
6. Implement and evaluate instructional materials considering mental models
7. Revise instructional materials


2. Conduct mental model analysis
Identify knowledge and skills through existing texts/documents and subject matter experts
Determine if mental model strategy would be helpful
Is mental model strategy helpful?
y
n
Get experts, intermediates, and/or novices' mental models
Determine relevant mental models to teach
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